



Importance of Growth Regulators and Growth Retardants on Growth, Yield and Economics of Pigeonpea (*Cajanus cajan* L.): A Review

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ABSTRACT

Pigeonpea (*Cajanus cajan* L.) is a notable pulse crop that is cultivated in the tropical and subtropical zones, which is regarded not only in terms of food security but also in terms of improved soil fertility and as a source of income among the smallholder farmers. Its productivity is, however, low because of biotic and abiotic stresses, bad crop management and low adoption of better agronomic practices. The concept of using plant growth regulators (PGRs) and growth retardants has been seen as a successful method to stimulate crop growth, crop yield and economic benefits by controlling physiological and morphological characteristics. PGRs, including auxins, gibberellins and cytokinins, are used at different stages of growth to induce the division of cells, elongate cells, flowering, pod development and uptake of nutrients. Chlormequat chloride (CCC), paclobutrazol and maleic hydrazide are growth retardants that regulate excessive vegetative growth and enhance flowering and modify assimilate partitioning in favor of reproductive organs. Concentration, timing and environmental conditions are optimized to ensure that there are good responses in various agro-ecological conditions. Research has demonstrated that the use of moderate amounts of PGRs and retardants improves yield parts, such as the number of pods per plant, the number of seeds per pod, seed weight and overall yield. They also enhance photosynthetic performance, biomass growth, protein level and harvest index by inhibiting apical dominance and enhancing reproductive growth. By and large, growth regulators and retardants enhance productivity, profitability and efficiency of resource utilization in pigeonpea farming, but optimization to suit the regions is critical to reap the long-term gains.

Key words: Economics, Growth regulators, Growth retardants, Pigeonpea, Plant physiology, Productivity, Yield.

Pigeonpea (*Cajanus cajan* L.) is an important legume crop, particularly in tropical and subtropical areas, which has been of great importance to humans due to its rich protein content and also due to its adaptation to marginal environments. Its productivity is, however, limited by mostly abiotic stresses like drought, salinity and extreme temperatures, which may severely affect the growth and yield. In that matter, plant growth regulators (PGRs) and growth retardants have become major tools of contemporary agronomy to maximise crop output and economic gain. Organic compounds include PGRs: auxins, gibberellins, cytokinins, abscisic acid, ethylene, brassinosteroids, jasmonates, salicylic acid and polyamines, which, at low concentrations, have far-reaching effects on plant physiological functions, e.g., cell division, plant growth, flowering, fruit set, or stress adaptation. PGRs have also been shown to promote seed germination, growth of roots and shoots, photosynthetic efficiency and antioxidant defences when exogenously administered and thus improve yield and quality, especially during stress experiences such as salinity and drought (Quamruzzaman *et al.*, 2021; Shah *et al.*, 2023; Zhang *et al.*, 2021; Jangra *et al.*, 2022; Shafi *et al.*, 2025). Indicatively, gibberellic acid (GA₃) has been known to facilitate numerous facets of plant growth and development and its application can correct the adverse impacts of abiotic stresses by modifying physiological and biochemical functions, eventually leading to improved yield

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and crop quality (Shah *et al.*, 2023). Likewise, it is known that polyamines facilitate organogenesis and increase stress resistance, as well as cellular metabolism, which

subsequently lead to better plant development and resistance (Jangra *et al.*, 2022).

Growth retardants, on the other hand, are applied to check surplus vegetative growth, lessen lodging and divert assimilates to the reproductive organs, which may stabilize or even boost yields. The efficacies of PGRs and growth retardants are very context-specific and include such aspects as crop genotype, time, dosage and environmental factors (Quamruzzaman *et al.*, 2021; Shafi *et al.*, 2025). The advantages of such substances are apparent in the form of better growth and yield, but their economic capacity should be taken into account as well. The prices of PGRs and a limited scope of their effective implementation may constrain their practical implementation, particularly in field conditions in which the variation of the environment can be quite high and the cost-benefit ratio may not necessarily justify their use (Quamruzzaman *et al.*, 2021). However, growth regulators and retardants could be used to improve the efficiency of resource use, reduce the negative impact of stresses on the environment and yield benefits and thus the economic sustainability of growing pigeonpea. This necessitates the complexity of the interaction among various PGRs with their signaling pathways and crosstalk with other plant hormones to use them optimally and gain the most benefits in pigeonpea production systems (Quamruzzaman *et al.*, 2021; Shah *et al.*, 2023; Jangra *et al.*, 2022; Shafi *et al.*, 2025). With further research that is still underway to demystify not only the molecular and physiological processes that PGR action, but the combination of these processes in pigeonpea agronomy is also expected to increase productivity, resilience and profitability as the environmental pressures continue to increase.

Plant growth regulators (PGRs) as central orchestrators of crop physiology

Plant growth regulators (PGRs) or phytohormones are a wide range of natural or synthetic organic compounds, which significantly affect almost all plant physiological processes, growth and environmental acclimatization, even

at low dosages (Fig 1). These molecules are signaling molecules: auxins, cytokinins, gibberellins, abscisic acid, ethylene, brassinosteroids, jasmonates, salicylic acid and strigolactones, that coordinate multiplex networks that regulate cell division, elongation, differentiation, organogenesis, flowering, fruit set, ripening and senescence. PGRs play a central role in regulating the response of plants to both biotic and abiotic stresses like drought, salinity, temperature extremes, heavy metal toxicity, among others, to protect crop productivity and quality in harsh environments (Shafi *et al.*, 2025; Shah *et al.*, 2023; Quamruzzaman *et al.*, 2021; Shah *et al.*, 2021; Li *et al.*, 2020). To give an example, gibberellic acid (GA₃) plays a crucial role in seed germination, stem and fruit growth and the exogenous application of this compound can alleviate the stress of abiotic factors, regulating physiological and biochemical processes, improving antioxidant defences and promoting yield and after-harvest quality (Shah *et al.*, 2023; Castro-Camba *et al.*, 2022).

Cytokinins control cell division and differentiation, affect yield and are also significant in stress responses through complex signalling cascades (Li *et al.*, 2020). The central role of auxins is known in the process of cell elongation, root development and tropic response and their interaction with calcium signaling and other PGRs is the basis of plant growth and adaptation (Zhang *et al.*, 2022). Another type of PGRs is brassinosteroids, which oversee cell expansion, morphogenesis and stress tolerance by changing the expression of genes and improving antioxidant, but frequently interacts with other hormones (Shah *et al.*, 2024; Napieraj *et al.*, 2023). Absciscic acid (ABA) is a global controller of the plant adaptation to water scarcity and salt, which coordinates the stomatal closure, osmotic adaptation and expression of stress-related genes (Shafi *et al.*, 2025; Quamruzzaman *et al.*, 2021; Zhang *et al.*, 2021). Jasmonates and salicylic acid also play a significant role in pathogen defence and wounding and environmental stressor responses (Hirayama and Mochida, 2022; Napieraj *et al.*, 2023). Physiological PGRs affect dynamic crosstalk and feedback

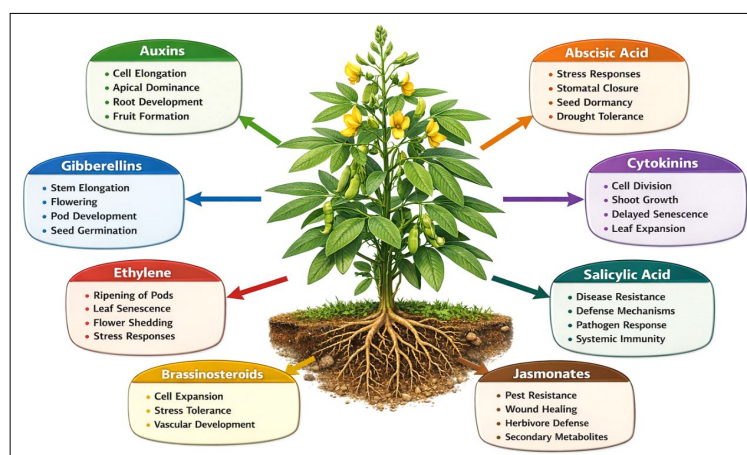


Fig 1: Plant growth regulators as central orchestrators of crop physiology.

of various hormone pathways and this enables plants to tightly regulate their growth and stress responses based on the developmental stage and environmental signals (Shafi *et al.*, 2025; Quamruzzaman *et al.*, 2021; Li *et al.*, 2020; Shah *et al.*, 2024; Hirayama and Mochida, 2022; Castro-Camba *et al.*, 2022).

PGRs seem to be a significant method of crop management nowadays, providing effective tools to promote growth, yield and stress resistance of crops, particularly in fruit, oil and cereal crops (Shah *et al.*, 2023; Quamruzzaman *et al.*, 2021; Shah *et al.*, 2021; Gill *et al.*, 2022; Zhang *et al.*, 2024; Singh *et al.*, 2024). Nevertheless, the positive impacts of PGRs are very context-specific and depend on genotype, timing, dosage and environmental factors and the practical use of PGRs must be optimized to avoid adverse outcomes or economic unproductiveness (Quamruzzaman *et al.*, 2021; Shah *et al.*, 2021; Zhang *et al.*, 2021). The development of plant hormonomics and molecular genetics revealed that allele differences in hormone-related genes can be used to breed climate-tolerant, high-yielding types of crops, such as the semi-dwarf wheat and rice developed during the Green Revolution, which were the result of mutations in gibberellin and brassinosteroid-related genes (Hirayama and Mochida, 2022). Moreover, PGRs can also engage with microbes that are associated with plants, including plant growth-promoting rhizobacteria, which have the potential to regulate the endogenous hormone levels and improve stress tolerance, providing new opportunities to enhance sustainable crop development (Hirayama and Mochida, 2022; Zhang *et al.*, 2021). In short, it is impossible to overestimate the importance of PGRs in the regulation of crop physiology, as they are the ultimate integrators of growth, development and adaptation to the environment and their responsible use and genetic engineering have the potential to be of invaluable complement to the global food security and climate change challenges.

Commonly used growth regulators and retardants in pigeonpea

Growth regulators and retardants are commonly used and are vital in maximizing the growth, development and stress endurance of pigeonpea (*Cajanus cajan* L.), which eventually contributes to the high yields and quality of crops. Plant growth regulators (PGRs) are naturally occurring phytohormones as well as artificial substances that modulate plant physiological activities at very low concentration levels. The PGRs used most commonly in pigeonpea are auxins, cytokinins, gibberellins (astrhogibberellic acid, GA₃), abscisic acid (ABA), ethylene, brassinosteroids, jasmonates, salicylic acid and polyamines. All these regulators play a unique role: auxins support root growth and elongation of cells; cytokinins stimulate cell division and inhibit leaf senescence; gibberellins stimulate seed germination, stem elongation and organ development; ABA is essential in stress response, particularly during drought and salinity; ethylene supports fruit ripening and stress

adaptation; brassinosteroids and jasmonates regulate growth and defense development; salicylic acid supports growth and stress resistance; and polyamines support cell division, membrane stability and stress tolerance (Quamruzzaman *et al.*, 2021; Shah *et al.*, 2023; Jangra *et al.*, 2022) (Table 1).

Excessive vegetative growth, lodging and redirection of assimilates to reproductive organs are controlled by the use of growth retardants (triazoles and quaternary ammonium compounds) to stabilize or increase yield. Their activity is affected by such factors as the genotype, the time, the dosage and the environmental features and the proper application of these substances could result in a considerable increase in the production and the economic gains of crops. Nevertheless, their effective use should be handled with caution because of small effective margins and possible adverse effects in the case of improper use (Quamruzzaman *et al.*, 2021; Shah *et al.*, 2023). The following table highlights the key growth regulators and retardants that are widely applied to pigeonpea, their key roles and well as in managing crops.

Effect of growth regulators on vegetative growth

Plant growth regulators (PGRs) have an extensive influence on vegetative growth, which determines the architecture of plants, biomass growth and development of major plant organs, including leaves, stems and roots. PGRs: the auxins, cytokinins, gibberellins, abscisic acid, ethylene, brassinosteroids, jasmonates and salicylic acid are signalling molecules that regulate complex physiological and molecular processes that allow plants to adapt to stimulating and adverse environments. As an example, gibberellic acid (GA₃) is extensively documented to induce cell elongation and division, thereby resulting in accelerated stem and leaf growth and reducing the adverse impact of abiotic stresses by regulating metabolic and antioxidant signalling, thus facilitating a healthy vegetative growth (Hanumanthappa *et al.*, 2018; Shah *et al.*, 2023; Shah *et al.*, 2021; Quamruzzaman *et al.*, 2021). The cytokinin plays a central role in the control of cell division and shoot development and the interaction with other hormones, such as auxins and gibberellins, also provides a fine spectrum of regulation between the root and shoot development to achieve optimal plant morphology and functionality (Li *et al.*, 2020; Quamruzzaman *et al.*, 2021).

GRFs are a family of evolutionally conserved growth-regulating factors (GRFs) that are involved in the growth of leaves, roots and flowers, enhancement of the grain filling process and organ size and weight and in the growth of organ size and weight. An example of these miR396-GRF-GIF regulatory modules controls the expression of vegetative organs development-related genes and their manipulation has been demonstrated to increase leaf development and shoot production, which are crucial factors in plant productivity (Liu *et al.*, 2022). Strigolactones and brassinosteroids are also important modulators of root and shoot architecture that act in crosstalk with auxins

and nitric oxide and affect lateral and adventitious root development in addition to helping the plant to overcome environmental stressors (Altamura *et al.*, 2023). PGRs have a strong context-dependent effect on vegetative growth and the outcome of the process is determined by the genotype, developmental stage, the environmental condition and the time and concentration of application (Quamruzzaman *et al.*, 2021). Although exogenous PGRs application can produce substantial growth and biomass, they can be the most effective when used in combination with the knowledge of endogenous hormone signalling and the physiological condition of the plant. Additionally, various PGRs can lead to synergistic or antagonistic effects in the presence of each other, which implies the need to manage them with extreme care in order to obtain the desirable growth results (Quamruzzaman *et al.*, 2021; Li *et al.*, 2020). To conclude, the growth regulators are essential instruments to control the vegetative growth to enable plants to develop the optimal architecture, resource distribution and resiliency, which are the drivers of high productivity and adaptability to various agricultural systems (Liu *et al.*, 2022; Shah *et al.*, 2023; Shah *et al.*, 2021; Li *et al.*, 2020; Quamruzzaman *et al.*, 2021; Altamura *et al.*, 2023).

Impact of PGR on flowering, reproductive development and pod formation

The use of plant growth regulators (PGRs) has a great impact on flowering, reproductive growth and pod formation in crops through the control of hormonal balances, gene expression and physiological mechanisms. An example of this is gibberellic acid (GA_3), which enhances pollen viability, fruit and pod set and promotes the floral initiation process, particularly in abiotic stress conditions, including salinity and drought, to increase the overall yield and quality (Shah *et al.*, 2023; Quamruzzaman *et al.*, 2021; Shah *et al.*, 2024) (Table 2). The involvement of cytokinins in reproductive development involves a central role in floral meristems, the number of flowers and pod development and the interaction of cytokinins with other hormones, such as auxins and gibberellins, is associated with the time and successful reproductive development (Li *et al.*, 2020). Brassinosteroids are also becoming new players in flowering and fruit development and increasing the yield and set of pods by regulating gene expression and improving the tolerance of stress (Quamruzzaman *et al.*, 2021; Shah *et al.*, 2024). Another group of growth regulators

Table 1: Common growth regulators and retardants in pigeonpea.

Regulator/retardant	Main function(s)	Role in pigeonpea management	Citations
Auxins (e.g., IAA)	Root development, cell elongation	Promotes rooting, improves nutrient uptake	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023; Jangra <i>et al.</i> , 2022)
Cytokinins	Cell division, shoot initiation, delay senescence	Enhances shoot growth, delays aging	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023; Jangra <i>et al.</i> , 2022)
Gibberellins (GA_3)	Seed germination, stem elongation, organ growth	Boosts growth, mitigates stress effects	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023)
Absciscic acid (ABA)	Stress response, stomatal closure	Enhances drought/salinity tolerance	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023; Jangra <i>et al.</i> , 2022)
Ethylene	Fruit ripening, stress adaptation	Regulates maturation, stress signaling	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023; Jangra <i>et al.</i> , 2022)
Brassinosteroids	Cell expansion, stress tolerance	Improves growth, enhances stress resilience	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023; Jangra <i>et al.</i> , 2022)
Jasmonates	Defense, growth modulation	Enhances stress and pest resistance	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023; Jangra <i>et al.</i> , 2022)
Salicylic acid	Growth, stress resistance	Promotes growth, boosts defense responses	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2023; Jangra <i>et al.</i> , 2022)
Polyamines	Cell division, membrane stability, stress tolerance	Improves growth, mitigates stress	(Jangra <i>et al.</i> , 2022)
Triazoles (retardant)	Inhibits gibberellin biosynthesis, reduces height	Controls overgrowth, reduces lodging	(Shah <i>et al.</i> , 2023)
Quaternary ammonium compounds (retardant)	Prevents lodging, minimal residue	Stabilizes yield, safe for soil	(Shah <i>et al.</i> , 2023)

is polyamines, which are associated with the development of floral organs and pollen tubes and fertilization, leading to successful pod formation and seed development (Jangra *et al.*, 2022; Napieraj *et al.*, 2023). The time of flowering, fruit set and seed development is also synergistically regulated by melatonin and indole-3-acetic acid (IAA), but melatonin enhances flowering and IAA aids in the growth and development of reproductive organs and pod filling (Zhang *et al.*, 2022). The impact of PGRs, however, is very specific and it depends on the genotype, the conditions of the environment, timing and concentration of application and misuse of these substances may have adverse effects such as lower fertility or abnormal development (Wang and Hao, 2023; Quamruzzaman *et al.*, 2021). The following Table 2 provides a summary of the key PGRs and their reported effects on the flowering, reproductive development and pod-forming processes.

Influence on yield attributes and productivity

The effect of plant growth regulators (PGRs) on yield characteristics and general output is immense because these substances coordinate essential physiological, biochemical and growth pathways that have a direct effect on crop production. PGRs like auxin, gibberellin, cytokinin, abscisic acid, ethylene, brassinosteroid and salicylic acid control the expression of the endogenous hormone, optimize photosynthesis and improve the transport and partitioning of assimilates and this way improve the source-sink relationship in plants (Amoanimaa-Dede *et al.*, 2022; Zhang *et al.*, 2024). This optimization results in the increase of key yield parameters such as the number of pods or fruits, grain or seed size, seed weight and biomass in general, which all contribute to the ultimate yield (Amoanimaa-Dede *et al.*, 2022). As an example, gibberellic acid (GA₃) has been demonstrated to enhance seed germination, phenotypic characteristics and metabolic processes leading to increased yield and improved quality of various crops, particularly in abiotic stress conditions,

including drought, salinity and temperature extremes (Shah *et al.*, 2023; Shah *et al.*, 2021; Shah *et al.*, 2024). Equally, cytokinins and brassinosteroids are crucial in improving reproductive development, fruit set and seed filling and they also aid in the improvement of yield (Zhang *et al.*, 2024; Shah *et al.*, 2024).

The PGRs are especially useful in the reduction of the adverse impact of environmental stresses because they assist in preserving the redox homeostasis and regulating the ionic transport as well as the activation of antioxidant defences, which are significant to maintain productivity under less-than-optimal conditions (Shah *et al.*, 2023; Quamruzzaman *et al.*, 2021; Shah *et al.*, 2021; Shah *et al.*, 2024). PGRs have been found to enhance yield, pod set, seed number and seed weight in legumes and oilseed crops; in addition, PGRs have been observed to improve the quality of the crop (e.g., protein and oil content) (Amoanimaa-Dede *et al.*, 2022; Shah *et al.*, 2021). Nevertheless, the positive impact of PGRs is strongly affected by the crop species, genotype, time, concentration and environmental factors and requires adequate management to ensure all the productivity increase and to prevent the possible adverse effects (Amoanimaa-Dede *et al.*, 2022; Quamruzzaman *et al.*, 2021; Zhang *et al.*, 2024). However, the discovery of plant hormonomics and molecular genetics has also made it possible to identify and manipulate genes associated with hormones, resulting in high-yielding, stress-tolerant varieties of crops, including the semi-dwarf wheat and rice of the Green Revolution, which was the result of modified gibberellin and brassinosteroid pathways (Hirayama and Mochida, 2022). Although the economic aspect of the use of some PGRs, e.g., brassinosteroids, may restrict the cost-effectiveness and practicality of their use, the possibility of an increase of yield by 10-15 million tons per year highlights the importance of such hormones in current agriculture (Amoanimaa-Dede *et al.*, 2022; Quamruzzaman *et al.*, 2021).

Table 2: Key growth regulators on flowering, reproductive development and pod formation.

Growth regulator	Documented effects on flowering and reproduction	Citations
Gibberellic Acid	Promotes floral initiation, pollen viability, pod/fruit set	(Shah <i>et al.</i> , 2023; Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2024)
Cytokinins	Stimulate floral meristem, increase flower/pod number	(Li <i>et al.</i> , 2020; Quamruzzaman <i>et al.</i> , 2021)
Brassinosteroids	Enhance pod yield, seed set, stress resilience	(Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2024)
Polyamines	Support floral organ development, pollen tube growth, fertilization	(Jangra <i>et al.</i> , 2022; Napieraj <i>et al.</i> , 2023)
Melatonin and IAA	Regulate flowering time, fruit set, seed development	(Zhang <i>et al.</i> , 2022)
General PGRs	Modulate gene expression, improve reproductive success under stress	(Shah <i>et al.</i> , 2023; Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2024)
Overuse/Improper Use	Can reduce fertility, cause abnormal development	(Wang and Hao, 2023; Quamruzzaman <i>et al.</i> , 2021)

Growth retardants and lodging resistance

The use of growth retardants in agriculture is common to improve the lodging resistance, which is an important aspect of sustaining crop yield and quality in the cases of cereals and other tall crops. Lodging: The long-term outgrowth of stems or roots out of their straight position by wind, rainfall, or too much vegetative development may result in great losses of yields and make mechanical harvesting more difficult. Growth retardants (also plant growth retardants (PGRs) act mainly by suppressing gibberellin synthesis or activity, as well as in certain instances, brassinosteroid (the hormone involved in the elongation of stems) (Fig 2). These compounds decrease the centre of gravity of the plant by reducing internode length and total plant height and reducing the likelihood of bending and breaking of stems when exposed to stress (Niu *et al.*, 2021; Niu *et al.*, 2022; Shah *et al.*, 2021). Examples of frequently used growth retardants are the triazoles (paclobutrazol and uniconazole), quaternary ammonium compounds, cyclohexane carboxylic acid derivatives (prohexadione-calcium) and succinic acid derivatives (B9). Triazoles are specifically successful, especially in reducing the height of the plant, but also increasing the stem diameter as well as lignin content to make the stem stronger, thus adding more resistance to lodging. Nevertheless, they may be problematic for further crops due to the longstanding soil residue that should be managed (Li *et al.*, 2024; Shah *et al.*, 2021). The advantages of quaternary ammonium compounds are based on their ability to prevent lodging without leaving harmful soil and so they are a safer choice when employed with moderate doses (Li *et al.*, 2024).

Carboxylic acid types of cyclohexane are easy to decompose in soil, though their use should be controlled to prevent the possibility of toxicity, whereas the use of B9 is also restricted because it is highly toxic (Li *et al.*, 2024). Besides the use of chemical growth retardants, more genetic strategies have worked: breeding for semi-dwarfism and higher lignification of stems, as in the

example of the successful Green Revolution using semi-dwarf cereal varieties (Niu *et al.*, 2021; Niu *et al.*, 2022). The most suitable plan is to integrate the practice of growth retardants with genetic enhancement and agronomics to achieve the highest growth of the plants in terms of height, strength of stems and canopy structure to ensure maximization of lodging resistance without reducing yield and biomass production (Niu *et al.*, 2021; Niu *et al.*, 2022; Shah *et al.*, 2021). It is necessary to mention that in case of excessive vegetation reduction, the grain size, fertility and productivity may be adversely affected and the distribution of growth retardants should be recalculated to reach a compromise between the lodging resistance and yield potential (Niu *et al.*, 2021; Niu *et al.*, 2022). In general, growth retardants have become an inseparable part of the contemporary crop management framework, as they provide a viable solution to the reduction in lodging risk, the stabilization of yields, as well as the facilitation of efficient mechanized harvesting, should they be applied in a manner that is specific to the type of crop, environmental conditions and the long-term health of the soil (Li *et al.*, 2024; Niu *et al.*, 2021; Niu *et al.*, 2022; Shah *et al.*, 2021).

Interaction of PGRs with nutrient and water management

Plant growth regulators (PGRs) are dynamically governed by nutrient and water management strategies to achieve optimal plant growth, stress and productivity. PGRs (auxins, cytokinins, gibberellins, abscisic acid and brassinosteroids) control physiological functions that have a direct effect on nutrient uptake, water use efficiency and plant adaptation to abiotic stresses (drought and salinity). As an illustration, PGRs can be used exogenously to stimulate root growth and architecture, which facilitates the uptake of water and nutrients by the plant in the soil and also regulates stomatal conductance and photosynthetic efficiency to save water in stressful situations (Zhang *et al.*, 2021; Quamruzzaman *et al.*, 2021; Shah *et al.*, 2021; Math *et al.*, 2019). These effects are further enhanced by plant growth-

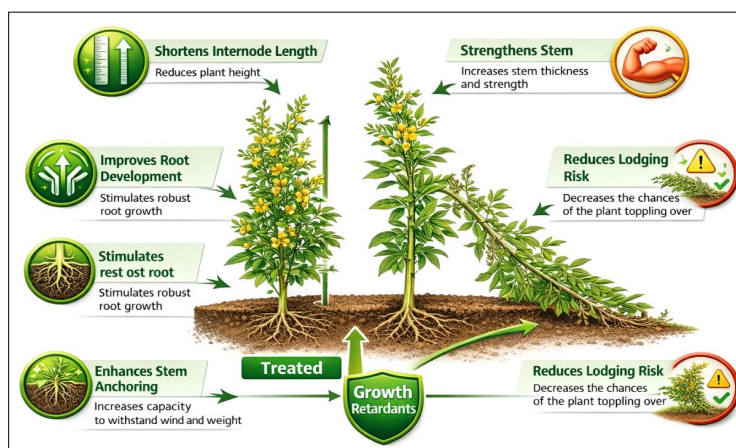


Fig 2: Growth retardant use for lodging resistance.

promoting rhizobacteria (PGPR), which are a form of biostimulant and synthesize phytohormones, solubilize nutrients (like phosphorus and potassium) and fix atmospheric nitrogen, therefore, increasing nutrient availability and uptake, especially under drought or nutrient-limiting conditions (Hamid *et al.*, 2021; Abdelaal *et al.*, 2021; Bechtaoui *et al.*, 2021). Silicon application, which is not a typical PGR, also affects hormonal pathways to enhance nutrient accumulation and water use efficiency, which increases drought resistance and the overall crop productivity (Rea *et al.*, 2022). The combination of PGRs with nutrient and water management is especially successful in reducing the adverse effects of environmental stresses because these regulators trigger antioxidant defences, osmotic homeostasis and changes to the gene expression associated with stress management (Zhang *et al.*, 2021; Quamruzzaman *et al.*, 2021; Shah *et al.*, 2021). The efficiency of such interactions, however, is dependent on species and genotype, timing and environmental conditions and it cannot be effectively calibrated, or its application may result in negative outcomes or cause inefficiencies (Quamruzzaman *et al.*, 2021; Shah *et al.*, 2021). Table 3 below shows the primary interrelations among PGRs, nutrient management and water management and the interplays of these elements in ensuring sustainable crop production.

Economic feasibility and cost-benefit analysis

The economic viability and the cost-benefit analysis of the application of plant growth regulators (PGRs) in agriculture is a multifactorial problem that varies with several factors, such as the kind of PGR, the species of crops, the environmental factors and the market prices. Although PGRs have the potential to improve crop performance, yield and stress tolerance, the use of these biological agents is limited by high cost, very specific effectiveness and

unreliable field responses. As an illustration, application of some of the PGRs, such as 24-epibrassinolide (EBL), in salt-stressed peas has been reported to raise yield by 18 to 35 percent. Nevertheless, EBL is excessively expensive and even with a significant increment in yield, the financial profit does not justify the investment cost: the application on a per-hectare basis can cost more than the increment in the revenue when the number of hectares is large, so it is economically unacceptable (Quamruzzaman *et al.*, 2021). EBL is not the only synthetic PGR whose cost-benefit balance may be inadequate, but appears to be more so in the case of other synthetic PGRs, as the supplementary costs of application technology and timing and variability in nature further restrict their practical usefulness when using them in the field (Quamruzzaman *et al.*, 2021; Pallavi *et al.*, 2020). Plant growth-promoting microorganisms (PGPR) and biostimulants, in contrast, are turning out to be increasingly economically viable options. These bioagents can decrease the usage of chemical fertilizers and pesticide application, reduce the input costs and enhance the crop resistance and output, which is a more sustainable and economical solution to farmers (El-Saadony *et al.*, 2022; Rouphael and Colla, 2020; De Andrade *et al.*, 2023; Hamid *et al.*, 2021).

PGPR and biostimulants have a specific benefit in the low-input or resource-constrained system where they can be applied to improve the efficiency of nutrient utilization and crop quality without the necessity of expensive synthetic PGRs (Rouphael and Colla, 2020; De Andrade *et al.*, 2023; Hamid *et al.*, 2021). Nevertheless, despite biostimulants, there are still issues with the formulation stability, production on a large scale and the stability of the field performance, which can impact the economic sustainability of biostimulants (Pellegrini *et al.*, 2020; Ansabayeva *et al.*, 2025). Finally, although PGRs and biostimulants may be very promising to enhance agronomical productivity, their

Table 3: Key Interactions of PGRs with nutrient and water management.

PGR/approach	Interaction with nutrient/ water management	Documented effects	Citations
Auxins, cytokinins, GAS	Enhance root growth, nutrient uptake, water absorption	Improved nutrient use efficiency, drought tolerance	(Zhang <i>et al.</i> , 2021; Quamruzzaman <i>et al.</i> , 2021; Shah <i>et al.</i> , 2021)
Absciscic acid (ABA)	Regulates stomatal closure, osmotic adjustment	Increased water use efficiency, stress resilience	(Zhang <i>et al.</i> , 2021; Quamruzzaman <i>et al.</i> , 2021)
Brassinosteroids	Modulate nutrient transport, stress signaling	Enhanced nutrient uptake, stress tolerance	(Shah <i>et al.</i> , 2021)
PGPR (biostimulants)	Fix N ₂ , solubilize P/K, produce phytohormones	Boosted nutrient availability, drought resistance	(Hamid <i>et al.</i> , 2021; Abdelaal <i>et al.</i> , 2021; Bechtaoui <i>et al.</i> , 2021)
Silicon application	Interacts with PGRs, improves nutrient accumulation	Higher nutrient uptake, water use efficiency	(Rea <i>et al.</i> , 2022)

economic viability should be carefully analyzed on a case-by-case basis, considering the cost of inputs, potential increase in the yield, market prices and agronomic conditions. In most instances, conventional breeding of crops based on stress tolerance and yield enhancement is still a sure and cost-efficient solution to reducing losses and maximizing returns, particularly in adverse environmental factors (Quamruzzaman *et al.*, 2021). In this way, they ought to be integrated into production systems by critical cost and benefit evaluation and must be specific to the needs and limitations of a particular production system (Quamruzzaman *et al.*, 2021; El-Saadony *et al.*, 2022; Rouphael and Colla, 2020; De Andrade *et al.*, 2023; Hamid *et al.*, 2021; Pellegrini *et al.*, 2020; Ansabayeva *et al.*, 2025).

Physiological and biochemical mechanisms behind growth regulation

A complex system of phytohormones, signalling proteins, transcription factors and small molecules coordinates plant growth regulation through the physiological and biochemical pathways that can also coordinate cellular processes, development and responses to environmental signals. The main part of this regulation is played by the phytohormones, namely, cytokinins, auxins (indole-3-acetic acid, IAA), gibberellins, jasmonic acid, brassinosteroids, abscisic acid and polyamines made with whose functions vary somewhat but mostly overlap. The cytokinins control development and stress responses through the activation of signal transduction pathways that regulate gene expression, leading to cell division, differentiation and adaptation to abiotic stresses such as drought and salinity. They further refine developmental responses and stress responses through their crosstalk with auxin, ethylene and gibberellin (Li *et al.*, 2020). Root and shoot development is regulated

synergistically by auxin and melatonin and auxin transport in the primary root of the plant is essential to form the primary root and melatonin in tolerance to tolerate stress. In low concentrations, melatonin enhances the production of IAA, whereas in high concentrations, it suppresses IAA, proving that it has a feedback loop that maintains a balance between growth and adaptation (Zhang *et al.*, 2022).

Gibberellic acid (GA₃) plays a critical role in seed germination, stem elongation and flowering and also reduces stress-induced perturbations through the adjustment of metabolic and redox processes (Shah *et al.*, 2023). Jasmonic acid (JA) and the interaction with other hormones such as abscisic acid (ABA) and brassinosteroids (BRs) balance the growth and defense and in unfavorable environments, the former often takes precedence over the latter (Wang *et al.*, 2020). Specifically, BRs increase cell division, cell elongation and resistance to stress through the action of gene expression and antioxidant defence (Shah *et al.*, 2024). The polyamines are involved in growth and adaptation by interacting with the phytohormones to mediate cell division, membrane stability and stress responses (Jangra *et al.*, 2022; Napieraj *et al.*, 2023). In addition to hormones, sugar-binding proteins like HXK, SnRK1 and TOR combine metabolic and energy signals and adjust cell proliferation, stomatal formation and adaptation to stress via complex signalling pathways (Li and Zhao, 2024). These regulatory networks are then further narrowed down to transcription factors (e.g., AP2/ERF, bHLH, CAMTAs) and small peptides to control gene expression based on hormonal and environmental signals (Abdel-Hameed *et al.*, 2024; Feng *et al.*, 2020; Wang *et al.*, 2021; Xiao *et al.*, 2025). The following Table 4 will outline the main regulators and their main physiological and biochemical processes in the regulation of plant growth.

Table 4: Key regulators and mechanisms in plant growth regulation.

Regulator/pathway	Main mechanisms and functions	Citations
Cytokinins	Signal transduction, gene regulation, cell division, stress response	(Li <i>et al.</i> , 2020)
Auxin (IAA) and melatonin	Root/shoot growth, auxin transport, stress adaptation, feedback	(Zhang <i>et al.</i> , 2022)
Gibberellins (GA _f)	Seed germination, stem elongation, metabolic/redox modulation	(Shah <i>et al.</i> , 2023)
Jasmonic acid (JA)	Growth-defense balance, crosstalk with ABA/BR, stress signaling	(Wang <i>et al.</i> , 2020)
Brassinosteroids (BRs)	Cell division/elongation, gene expression, antioxidant defense	(Shah <i>et al.</i> , 2024)
Polyamines	Cell division, membrane stability, hormone interaction, stress tolerance	(Jangra <i>et al.</i> , 2022; Napieraj <i>et al.</i> , 2023)
Sugar signaling (HXK, SnRK1, TOR)	Energy sensing, cell proliferation, stomatal development, stress adaptation	(Li and Zhao, 2024)
Transcription factors (AP2/ERF, bHLH, CAMTAs)	Gene expression control, hormone signaling integration	(Abdel-Hameed <i>et al.</i> , 2024; Feng <i>et al.</i> , 2020; Wang <i>et al.</i> , 2021; Niharika <i>et al.</i> , 2020)
Small peptides	Root meristem maintenance, cell division, stress resilience	(Xiao <i>et al.</i> , 2025)

Environmental and sustainability considerations

The future of agriculture is based on environmental and sustainability concerns because the industry is in a dilemma of expanding food production and, at the same time, reducing environmental degradation (Fig 3). Because of the conventional use of chemical fertilizers, pesticides and herbicides, agricultural activities have caused serious environmental concerns, such as soil erosion, water pollution, biodiversity loss and the emission of greenhouse gases, which pose risks to long-term commercial farming productivity and the well-being of the ecosystem (Baćmaga *et al.*, 2024; Zhou *et al.*, 2024; Meena *et al.*, 2020; Mng'ong'o *et al.*, 2021). The overuse of agrochemicals interferes with the microbial communities of the soil, decreases soil fertility and may lead to the development of toxic substances on the food chain, which is dangerous to human and animal health (Zhou *et al.*, 2024; Meena *et al.*, 2020; Mng'ong'o *et al.*, 2021). Conversely, plant growth-promoting rhizobacteria (PGPR), plant growth-promoting microbes (PGPMs) and microbial biostimulants may serve as an alternative solution with potential to promote sustainable farming systems because of their promising potential and their positive environmental impact (Ansabayeva *et al.*, 2025; Wahab *et al.*, 2024; Hamid *et al.*, 2021; Vishwakarma *et al.*, 2020; Elnahal *et al.*, 2022; De Andrade *et al.*, 2023; Malgioglio *et al.*, 2022). These beneficial microorganisms improve the health of soil, nitrogen cycling and tolerance of plants to abiotic stressors (drought, salinity, extreme temperatures) and reduce the use of synthetic inputs and decrease the environmental footprint of agronomy (Ansabayeva *et al.*, 2025; Wahab *et al.*, 2024; Hamid *et al.*, 2021; El-Saadony *et al.*, 2022; Vishwakarma *et al.*, 2020; Elnahal *et al.*, 2022; De Andrade *et al.*, 2023; Malgioglio *et al.*, 2022). PGPMs and PGPR aid in sustaining the soil biodiversity and ecosystem services by suppressing plant pathogens and enhancing nutrient uptake by plants in a natural manner that contributes to the long-term stability of the agroecosystem (Ansabayeva

et al., 2025; Wahab *et al.*, 2024; Hamid *et al.*, 2021; Elnahal *et al.*, 2022; Vishwakarma *et al.*, 2020).

In addition, greenhouse gases can be reduced by implementing microbial inoculants and biostimulants that will decrease the reliance on nitrogen-containing fertilizers and minimize nutrient leaching and runoff (Ansabayeva *et al.*, 2025; Wahab *et al.*, 2024; Hamid *et al.*, 2021; El-Saadony *et al.*, 2022; Vishwakarma *et al.*, 2020; Elnahal *et al.*, 2022; De Andrade *et al.*, 2023; Malgioglio *et al.*, 2022). Nevertheless, environmental conditions, including soil type, climate and the presence of microbial communities, can affect the efficacy of such biological solutions, which require site-specific solutions and additional studies to improve their use (Malgioglio *et al.*, 2022). This incorporation of sustainable measures is also aided by researchers developing biochar-controlled release fertilizers, which not only increase the efficiency of nutrient utilization but also improve the structure of the soil and sequester carbon and this further leads to the sustainability of the environment (Palansooriya *et al.*, 2025). In spite of these improvements, there are still challenges, such as the requirement to have sound regulatory frameworks, economic viability and reliable field performance of biostimulants and microbial products (Palansooriya *et al.*, 2025; Elnahal *et al.*, 2022; Malgioglio *et al.*, 2022).

Research gaps and future prospects in plant biostimulant and growth regulator research

Although a lot has been achieved in terms of the creation and use of plant biostimulants and growth regulators to ensure sustainable agriculture, there are still numerous research gaps that influence the future of research and development. The first of the gaps is the insufficient knowledge and commercial realization of microalgal biostimulants in comparison with those of macroalgae. The difficulties involved in the successful commercialization of microalgal products include identification and selection of the most suitable strains, metabolome coverage to discover new biological compounds, the necessity of

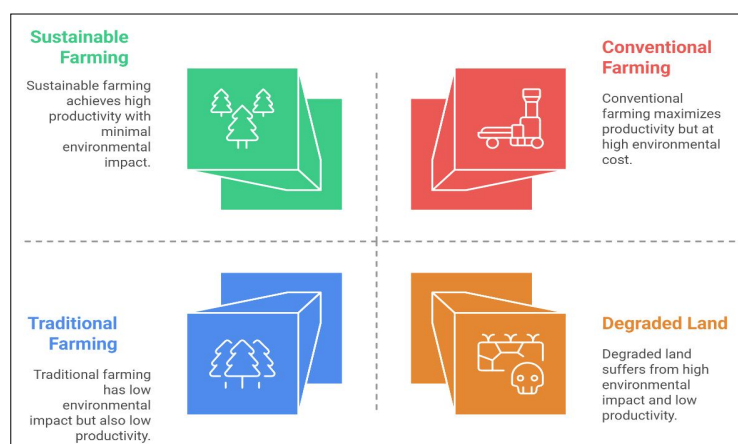


Fig 3: Balancing agricultural productivity and environmental sustainability.

efficient and sustainable methods of extracting them and the overall lack of effective understanding regarding genetic and molecular biosynthetic pathways in algae and algal-bacterial consortia. Besides, the changes in the composition and efficacy of microalgal extracts caused by seasonal variation and harvesting time have not been well studied yet, nor have the economic and lifecycle issues that would make it viable to scale up production within the context of the circular economy (Kapoor *et al.*, 2021; Chabili *et al.*, 2024; Prisa and Spagnuolo, 2023). Overall, in the wider framework of biostimulants, it is highly desirable that stricter field tests should be undertaken to confirm laboratory results since most of the studies performed are either in controlled or greenhouse situations and it has not been ascertained whether they represent the real-life agricultural conditions. The physiological and molecular pathways of the action of biostimulants, in particular in terms of plant-microbe and plant-environment interactions, are not yet thoroughly identified, which makes it impossible to optimize formulations and application regimes depending on crops and stress conditions (Rouphael and Colla, 2020; Zhang *et al.*, 2021; Nepali *et al.*, 2020; Shahrajabian *et al.*, 2023).

Moreover, the application of sophisticated omics methods, including metabolomics and high-throughput phenotyping, remains in its early stages, yet has the potential to unravel the enigmatic mechanisms of action and detect reliable biomarkers that reflect the effect of biostimulants on the body (Kapoor *et al.*, 2021; Nepali *et al.*, 2020). The absence of standardized definitions, quality control protocols and a set of rules regarding biostimulant products also poses a challenge because, in such cases, it becomes difficult to accept them by farmers and other stakeholders in the industry (Kapoor *et al.*, 2021; Rouphael and Colla, 2020; Chabili *et al.*, 2024). Moving forward, it is recommended that future studies should focus on the creation of strong, scalable and economically feasible biostimulant products and in this context, the main priorities should be put on the optimization of strain selection, the advancement of extraction and formulation technologies and the combination of biostimulants with other sustainable farming methods, including biofertilizers and nanotechnologies (Kapoor *et al.*, 2021; Chabili *et al.*, 2024; Magnabosco *et al.*, 2023). It is also necessary to discuss the socio-economic and environmental implications of the application of biostimulants regarding the health of soil, biodiversity and food safety and the acceptance of the products and their integration into the market (Hernández *et al.*, 2024; Magnabosco *et al.*, 2023).

CONCLUSION

The use of growth regulators and growth retardants in the production of pigeon pea has had a significant impact on augmenting the growth of the plants, yield characteristics and overall increment of the economic profits. These growth

regulators include the cytokinins and auxins, which stimulated vegetative growth, flowering and pod development and enhanced grain yield. Growth retardant, however, helped to control the unwanted excessive growth of vegetation to the advantage of more preferable assimilation of its partitioning to reproductive parts, thus improving the index of harvest and yield efficiency. They possessed balanced application to maximize the plant architecture and reduce lodging and enhanced stress tolerance, particularly in poor growing conditions. According to the economic terminology, the appropriate regulators of pigeonpea growth in terms of treatments also achieved higher net returns and benefit-cost ratios; hence, it is a possible sustainable tool of pigeonpea production. The correct dosage, timing and environmental conditions determine the effectiveness of these chemicals on the success of these chemicals, however. Therefore, the management of nutrient and growth controls regulators coordinated with crop stage need-based needs can have a huge contribution in the optimization of yield and profit. Additional research on the same regarding geographical-specifications and lasting effects is required to ensure that these chemicals are being administered safely and effectively in the production of pigeonpea.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

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